Scientific Frontiers in Research on Extrasolar Planets
ASP Conference Series, Vol. 294, 2003
D. Deming and S. Seager, eds.

Photometric Simulation of Transiting Extrasolar Planets

B. L. Lee and H. K. C. Yee

Dept. of Astronomy and Astrophysics, University of Toronto, 60 St. George Street, Toronto, ON, M5S 3H8, Canada

G. Mallén-Ornelas

Princeton University Observatory, Peyton Hall, Princeton, NJ 08544-1001 / Depto. de Astronomia y Astrofisica, P. Universidad Catolica de Chile, Casilla 306, Santiago 22, Chile

S. Seager

Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540 and The Carnegie Institution of Washington, Dept. of Terrestrial Magnetism, 5241 Broad Branch Rd. NW, Washington, DC 20015

Abstract. Photometric occultation simulations have been created for the EXPLORE project, a deep search for transiting extrasolar planets. We begin our transit simulations at the image level by adding simulated stars, some of which have light curves with transits, to actual images from the EXPLORE searches. By examining EXPLORE's performance in blind tests of transit recovery from these simulated data, we probe the bounds of EXPLORE's planet-finding capabilities. Such simulated detection statistics will provide completeness corrections for planet detections, or limits on types of planetary systems that are not detected. The accuracy of the derived detection statistics is maximized by matching both the data quality and analysis procedure for the simulations with the real data. Precision image quality mimicry is achieved using a set of well-characterized template stars and a "copy-and-paste" method. We present the simulation procedure and some preliminary results on the recovery of simulated transiting planets.

1. Introduction

Observations for the EXPLORE (EXtrasolar PLanet Occultation REsearch) Project are well underway, with early results released from the EXPLORE I transit search conducted in June 2001 at the CTIO 4-m telescope (Mallén-Ornelas et al. 2002). Future EXPLORE searches are planned, to discover more candidate extrasolar planetary transits.

In order to determine how significant any planet detections or non-detections that arise from EXPLORE searches are, we will need statistical tests of EXPLORE's planet-finding efficiency. Hence we need to simulate large samples of EXPLORE data seeded with artificial transits, to attempt to recover the transits in a blind analysis, and hence to derive our detection statistics. We have not yet implemented an automated transit-finding method, but in the meantime, we test the efficiency of human inspections for potential transits.

We create our simulations by modifying actual frames from the EXPLORE II search, a 14 night observing run conducted during December 2001 using the wide field (28' by 42') CFH12K camera at CFHT, with exposure times of 1 to 2 minutes (Yee et al. 2002; Mallén-Ornelas et al. 2003). By beginning our simulations at the image level, we account for not just statistical noise limits, but also the accuracy of the photometry. The simulated images are reduced to light curves using the same photometry pipeline utilized for the actual data (Mallén-Ornelas et al. 2002). We then carry out tests of our ability to spot simulated transits, as a function of transit depth and photometric accuracy, attempting to mirror the same detection capabilities as were applied to the real data.

2. Method of Simulation

To add simulated stars to actual EXPLORE data frames, we do not create them from scratch, as that would require us to explicitly calculate the PSF characteristics (which vary as a function of time because of atmospheric variation and telescope wobble, and as a function of coordinates because of the telescope optics). Rather, we use a "copy-and-paste" method: our added, simulated stars are simply modified versions of existing stars on the frames. By making simulations out of these real, "template" stars, we *implicitly* reproduce their PSFs.

Clearly, for this method to work, we should choose template stars which are stable representatives of the local PSF; crowded, variable, or very faint stars are unacceptable templates. These well-characterized template stars can be drawn from a set of reference stars integral to EXPLORE's photometry pipeline (hence always available in any EXPLORE data set).

Frame by frame, we find and copy each template star to a number of new locations in sky coordinates. Since the PSF varies slowly with coordinates, the copies must be placed near the template. A sinc-shift algorithm (Yee 1988) is used to resample from the sky coordinates to each frame's unique pixel grid.

Each simulated star thus created is multiplied by the appropriate value on a theoretical light curve, to simulate some or no variability. Poissonian noise characteristics are assumed (the stars are relatively faint, so scintillation noise is neglected) and preserved by the introduction of appropriate noise when needed.

The simulated images are processed via EXPLORE's photometry pipeline as if they were real data, so that our final light curves properly include the systematic error introduced in processing. The pipeline uses iterative sinc-shift centroiding to perform accurate small-aperture photometry, minimizing the sky noise contribution. Relative photometry is then performed to generate light curves. Photometric accuracy can reach 0.2% rms. The photometry is further described in the EXPLORE I preliminary results of Mallén-Ornelas et al. (2002). A sample of light curves is shown in Figure 1 (left panel). Four are derived from real stars, and one is derived from a simulated star which has been scaled down to 10% of its template's flux (but retains a flat light curve). Observe that it is not readily distinguished from the real stars of similar brightness: our simulations mimic the real data extremely well.

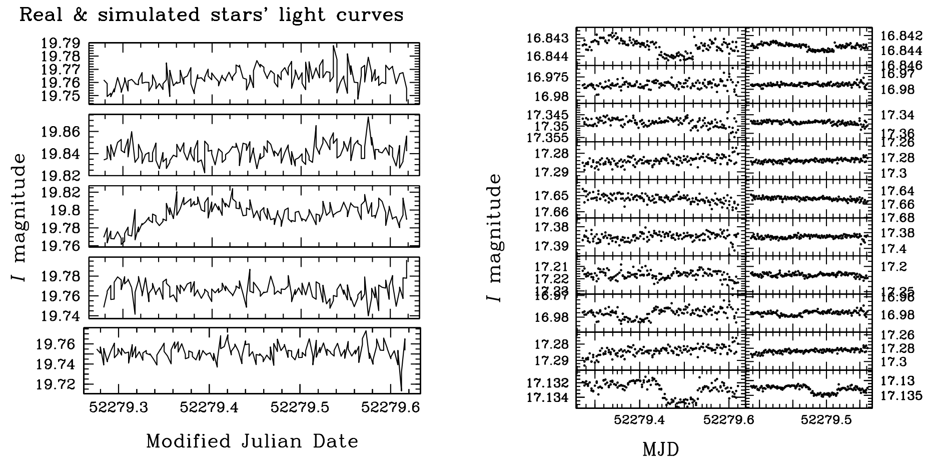


Figure 1. **Left panel:** These light curves show how well the noise characteristics of the real data are matched by the simulations. The second light curve from the top is a simulation; the others are derived from real stars. **Right panel:** A set of simulations including transits, presented in a tabular format mimicking the real, multi-night data (each light curve is presented at two zoom levels). Artificial transits were placed in the curves first, third, sixth, eighth, and tenth from the top.

For the preliminary analysis of the actual EXPLORE data, the light curves for a single star, spanning multiple nights, were displayed in a single plot and scanned for transits by eye. So, to mimic the appearance of true multi-night single star data and minimize possible human biases, we emulate this tabular format in our single-night preliminary simulations by using stacks of single-night light curves from several different simulated stars, some with artificial transits and some without (see Figure 1, right panel).

3. Results

Three members of the EXPLORE collaboration (those who scanned the actual data) scanned 990 simulated light curves in which 288 different transits were hidden, then submitted their picks for which light curves contained transits. The picks were scored, and the results (correct picks and missed transits) binned as a function of the light curves' rms and the transits' depths.

From their results, the EXPLORE collaborators were seen to be roughly equally conservative in their picks, making almost no incorrect picks. Because all three were similar, and because they all had been involved in scanning the actual data, detection statistics were derived based on the *average* detectability of the simulated transits.

The results form a two-dimensional surface in a three-variable space; it gives the fraction of times that an "average" EXPLORE collaborator will discover a transit, as a function of signal and noise. In this set of simulations, the signal

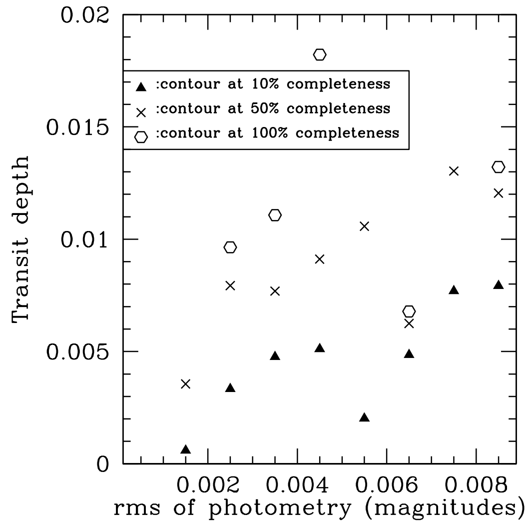


Figure 2. Slices from the EXPLORE group's averaged results, for 10%, 50%, and 100% completeness. The poor sample size is responsible for the jaggedness of the curves. Note for certain values of rms, 100% completeness was never reached.

strength was changed by varying the transit depth (up to 3%), and the noise was simply the rms (magnitudes) of the photometry (0.017 mag in the noisiest simulation performed). As one expects, the probability of transit detection (completeness) tends to increase with greater signal and decreases with greater noise. Figure 2 shows three slices through this two-dimensional surface, along contours of 10%, 50%, and 100% completeness.

For sure detection of simulated transits of 2% depth, high quality light curves ($\sim$ 0.005 mag rms) were needed. The best of EXPLORE's photometry does reach or surpass this accuracy, so these early simulations show that, when scanning such excellent light curves, we can achieve 100% completeness in detecting transit depths as small as 2%.

Our preliminary results have shown that by using our copy-and-paste image-based transit simulation, we can derive the selection function for EXPLORE's transit surveys. Future simulations will come even closer to reproducing all the conditions that influence transit identification in the real data. In particular, the introduction of multi-night light curves and more sources of non-transit variability should improve the validity of our derived detection statistics. We will also feed these simulations to automatic transit finding algorithms which are under construction.

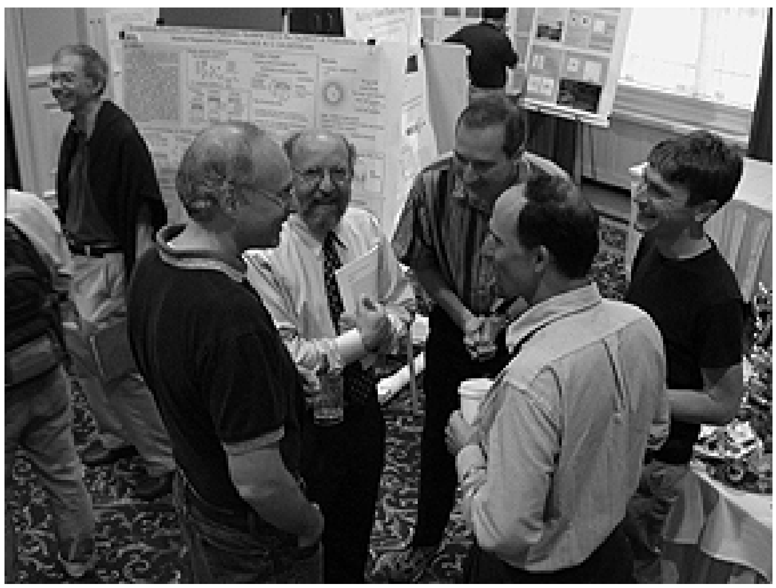
References

Mallén-Ornelas, G., Seager, S., Yee, H. K. C., Minniti, D., Gladders, M. D., Mallén-Fullerton, G. M., and Brown, T. M. 2002, submitted to ApJ, astro-ph/0203218

Mallén-Ornelas, G., Seager, S., Yee, H. K. C., Gladders, M. D., Brown, T. M., Minniti, D., Ellison, S. L., and Mallén-Fullerton, G. M. 2003, these proceedings

Yee, H. K. C., Mallén-Ornelas, G., Seager, S., Gladders, M., Brown, T., Minniti, D., Ellison, S., and Mallén-Fullerton, G. M. 2002, to appear in Proc. SPIE Conf.: Astronomical Telescopes and Instrumentation, astro-ph/0208355

Yee, H. K. C. 1988, AJ, 95, 1331



Discussions at the Poster Session